Defense Threat Reduction Agency
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TECHNICAL REPORT

Prompt Radiation Protection Factors

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This report presents the methodology and the results of calculation of the prompt radiation protection factors for various building types. The transport of prompt radiation was performed using the three dimensional Monte-Carlo radiation transport code MCNP (Monte Carlo N-Particle) and the evaluation of the protection factors (ratio of dose in the open to dose in the building) is based on simulated data from the propagation of prompt gammas and neutrons emitted from low yield thermonuclear device. Scattered radiation and secondary particles produced in the atmosphere, ground, and building structures are also taken into account in the simulations. The dose used for investigation of the protection factors was absorbed soft tissue dose considered to be better associated with acute, deterministic radiation effects.

15. SUBJECT TERMS
HPAC, prompt radiation, neutrons, gammas, radiation transport, MCNP, protection factors, absorbed dose

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UNIT CONVERSION TABLE

U.S. customary units to and from international units of measurement*

U.S. Customary Units	Multiply by → / ← Divide by†		International Units
Length/Area/Volume			
inch (in)	2.54	$\times 10^{-2}$	meter (m)
foot (ft)	3.048	$\times 10^{-1}$	meter (m)
yard (yd)	9.144	$\times 10^{-1}$	meter (m)
mile (mi, international)	1.609 344	$\times 10^{3}$	meter (m)
mile (nmi, nautical, U.S.)	1.852	$\times 10^{3}$	meter (m)
barn (b)	1	$\times 10^{-28}$	square meter (m^2)
gallon (gal, U.S. liquid)	3.785 412	$\times 10^{-3}$	cubic meter (m^3)
cubic foot (ft^3)	2.831 685	$\times 10^{-2}$	cubic meter (m^3)
Mass/Density			
pound (lb)	4.535 924	$\times 10^{-1}$	kilogram (kg)
unified atomic mass unit (amu)	1.660 539	$\times 10^{-27}$	kilogram (kg)
pound-mass per cubic foot (lbft^{-3})	1.601 846	$\times 10^{1}$	kilogram per cubic meter (kg m^{-3})
pound-force (lbf avoirdupois)	4.448 222		newton (N)
Energy/Work/Power			
electron volt (eV)	1.602 177	$\times 10^{-19}$	joule (J)
erg	1	$\times 10^{-7}$	joule (J)
kiloton (kt) (TNT equivalent)	4.184	$\times 10^{12}$	joule (J)
British thermal unit (Btu) (thermochemical)	1.054 350	$\times 10^{3}$	joule (J)
foot-pound-force (ftlbf)	1.355 818		joule (J)
calorie (cal) (thermochemical)	4.184		joule (J)
Pressure			
atmosphere (atm)	1.013 250	$\times 10^{5}$	pascal (Pa)
pound force per square inch (psi)	6.984 757	$\times 10^{3}$	pascal (Pa)
Temperature			
degree Fahrenheit (ºF)	[T(ºF) − 32]/1.8		degree Celsius (ºC)
degree Fahrenheit (ºF)	[T(ºF) + 459.67]/1.8		kelvin (K)
Radiation			
activity of radionuclides [curie (Ci)]	3.7	$\times 10^{10}$	per second (s$^{-1‡}$)
air exposure [roentgen (R)]	2.579 760	$\times 10^{-4}$	coulomb per kilogram (C kg^{-1})
absorbed dose (rad)	1	$\times 10^{-2}$	joule per kilogram (J kg$^{-1§}$)
equivalent and effective dose (rem)	1	$\times 10^{-2}$	joule per kilogram (J kg^{-1**})

*Specific details regarding the implementation of SI units may be viewed at http://www.bipm.org/en/si/.
†Multiply the U.S. customary unit by the factor to get the international unit. Divide the international unit by the factor to get the U.S. customary unit.
‡The special name for the SI unit of the activity of a radionuclide is the Becquerel (Bq). (1 Bq = 1 s^{-1})
§The special name for the SI unit of absorbed dose is the gray (Gy). (1 Gy = 1 J/kg^{-1})
**The special name for the SI unit of equivalent and effective dose is the Sievert (Sv). (1 Sv = 1 J/kg^{-1})

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Executive Summary

This document presents the methodology and the results of calculation of the prompt radiation protection factors for various building types in Hazard Prediction and Assessment Capability (HPAC) 6.5. The transport of prompt radiation was performed using the three dimensional Monte-Carlo radiation transport code MCNP (Monte Carlo N-Particle) and the evaluation of the protection factors (ratio of dose in the open to dose in the building) is based on simulated data from the propagation of prompt gammas and neutrons emitted from a low yield thermonuclear device. Scattered radiation and secondary particles produced in the atmosphere, ground, and building structures are also taken into account in the simulations. The dose used for investigation of the protection factors was absorbed soft tissue dose considered to be better associated with acute, deterministic radiation effects.

Prompt radiation protection factor values were calculated for 95 building types: 25 variations for 1-story buildings, 25 variations for 2-story buildings, 16 variations for 5-story buildings, 11 variations for 13-story buildings, and 18 variations for 50 story buildings.

The prompt radiation protection factors are calculated on the basement level (warned population in a building with basement), on the ground floor (warned population in a building with no basement), and on the above ground floors (unwarned population).

Depending on the characteristics of the buildings, the protection from prompt radiation ranges from 4.9 up to a factor of 258.4 on basement level, from 1.6 up to 28.3 on a first floor, and from 1.5 up to 13.5 on the above ground floors.

Section 1. Introduction

The threats to national security by detonation of a nuclear device have placed renewed emphasis on evaluation of the consequences in case of such an event. The Defense Threat Reduction Agency (DTRA) enables the Department of Defense and the U.S. Government to prepare for and combat weapons of mass destruction and improvised threats and to ensure nuclear deterrence.

DTRA develops and routinely uses the Hazard Prediction and Assessment Capability (HPAC) (Waller, et al. 2009) software package that provides chemical, biological, radiological and nuclear (CBRN) hazard prediction. DTRA's HPAC tool uses the Oak Ridge National Laboratory (ORNL) LandScan population database and previous to version 6.5 incorporated five distinct building types. To establish a more thoroughly justifiable methodology for HPAC's determination of casualties from prompt effects and to provide greater potential for detail in the determination of such, work was performed to assess prompt radiation Protection Factors (PFs) for any building types. These improvements in turn support the overall effort of improving HPAC consequence assessment and support a larger effort in collaboration with Lawrence Livermore National Laboratory (LLNL) and ORNL to develop a next-generation Regional Shelter Analysis (Dillon, et al. 2015) database of world-wide shelter quality.

This technical report presents the methodology proposed to evaluate the prompt radiation PFs. Complementary efforts were done to develop the fallout PFs (Dant, et al. 2018) and to update the methodology used for prompt casualty assessment from a nuclear detonation in HPAC6.5 (Wright, et al. 2018).

The sections of this report include the methodology of calculation of the prompt PFs, with a description of the buildings' design and computational model, results, and conclusions.

Section 2. Methodology

In the literature one can find numerous publications detailing PFs for delayed radiation or fallout (Dant, et al. 2018) (Defense Intelligence Agency 1992) but it is more difficult to find results or methodology developed for prompt radiation PFs evaluation (Glasstone and Dolan 1977). Our methodology for calculation of the prompt PFs is presented in this section. The computational method description includes the radiation sources and the dose conversion factors used in the MCNP (Monte Carlo N-Particle) (Goorley 2014) simulations followed by a sensitivity analysis of our model.

The evaluation of the prompt radiation PFs was performed using doses received from prompt nuclear radiation source, which includes prompt gammas, prompt neutrons, and neutron induced gammas (secondary gammas). These doses are all received practically in the same time, summing the effect of the prompt nuclear radiation. Since the PF is calculated from a building/receiver perspective in unshielded or shielded conditions, it doesn't matter exactly what type of radiation produces that dose; the receiver cannot see the difference in time or effect. While values for neutrons and gammas were calculated separately, the overall dose determines the prompt radiation PFs that are needed in HPAC. Having only the overall prompt radiation PF values is also simpler and more compact in the database. However values for neutron and gamma PFs are provided in this report in case the reader is interested to see the effect of different building types on shielding to neutrons for example or assuming there is an algorithm that is using the neutron and gammas PFs separately.

This report does not address initial radiation sources that would be emitted from the fireball and the radioactive cloud, often referred to as delayed radiation or latent radiation associated with fallout.

2.1. Protection Factor Calculation

The exposure to prompt nuclear radiation was quantified using absorbed soft tissue dose in the open and inside the buildings. The PF is calculated as a ratio of unshielded to shielded exposure to nuclear radiation (Equation 2.1), or in our case, the absorbed soft tissue dose in the open, D_0, over the absorbed soft tissue dose inside the building, D.

$$\boldsymbol{Protection\ Factor\ (PF) = \frac{Unshielded\ Exposure}{Shielded\ Exposure} = \frac{D_0}{D}} \qquad \textbf{2.1}$$

The unshielded exposure is calculated as absorbed soft tissue dose in the absence of the building while the shielded exposure is evaluated as absorbed tissue soft dose at the same reference height of 1 m above the floor inside the building (Figure 2.1).

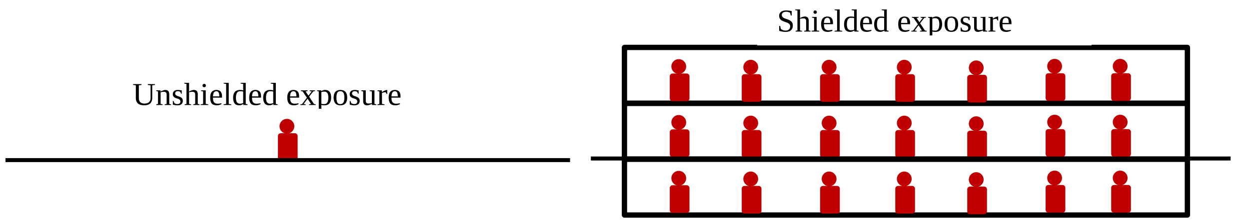

Figure 2.1 Shielded vs unshielded exposure

Three sets of PFs have been evaluated, corresponding to the following scenarios:

a) Warned population in a building with basement

People are assumed to be distributed evenly among all of the floors in a building except the basement which is assumed to be for storage only. When we have warned population means the people have time to move to a better shielded place. In this case an average PF was calculated considering the population occupying the building all having moved to the basement, following Equation 2.2 where N_B represents the number of meshes (or voxels) considered in the computational MCNP model at the basement level. The absorbed soft tissue dose that quantifies the exposure to radiation in our simulations is represented by D_0, the reference, unshielded (in the open) absorbed soft tissue dose, and D_i, the shielded at the basement level absorbed soft tissue dose in mesh i.

$$\boldsymbol{PF_{avg,warn} = PF_{avg,bas} = \frac{D_0}{D_{avg,bas}} = \frac{D_0}{\frac{\sum_{i=1}^{N} D_i}{N_B}}} \qquad 2.2$$

b) Warned population in a building without basement

In this scenario the building doesn't have basement so the warned population have time to move to the ground floor. An average PF was calculated considering the population occupying the building all having moved to the first floor, according to Equation 2.3 where N_{GF} represents the number of meshes considered in the computational MCNP model at the ground floor level. Here D_i represents the absorbed soft tissue dose in mesh i at first floor level.

$$\boldsymbol{PF_{avg,warn} = PF_{avg,1st} = \frac{D_0}{D_{avg,1st}} = \frac{D_0}{\frac{\sum_{i=1}^{N} D_i}{N_{GF}}}} \qquad 2.3$$

c) Unwarned population

Unwarned population means that people take no action. In this case the population occupying the building is distributed equally on all of the above ground floors, following Equation 2.4 where N_{AF} represents the number of meshes considered in the computational MCNP model for all the above ground floors and D_i is the absorbed soft tissue dose in mesh i, above ground level floors.

$$PF_{avg,warn} = PF_{avg,ab\ gr} = \frac{D_0}{D_{avg,ab\ gr}} = \frac{D_0}{\frac{\sum_{i=1}^{N} D_i}{N_{AG}}} \quad \mathbf{2.4}$$

The PFs are associated with buildings and the following section presents the building design characteristics (Dillon and Kane 2017).

2.2. Building Design

Protection factor values were calculated for 1-, 2-, 5-, 13-, and 50-story buildings with the following design assumptions (Dillon and Kane 2017):

- All buildings are square
- Interior mass is modeled as distributed foam columns in each room
- Every building was modeled with a basement
- Each floor is modeled with an opening to represent a stairway/elevator
- Each floor is 12 ft high and identical in design/layout except:
    - Only the first floor will have exterior doors
    - The basement will be completely underground
- Apertures:
    - Windows extend from 3 ft to 12 ft
    - Doors extend from ground level to 8.2 ft
    - Window densities are 3 pounds per sq ft (psf)
    - Door densities are 3 psf

All single story and two story buildings have a footprint of 1,000 sq ft and the taller buildings have a footprint of 10,000 sq ft.

Examples of materials used for exterior wall are presented in Table 2.1 in terms of live loads[1].

Table 2.1 Example materials for exterior walls

Density Category	Nominal psf	Materials
Extremely light	1.5	Lightweight Vegetation (1.5 psf) Wood Frame – Plastic Sheet (1.76 psf)
Light	10	Concrete Frame – No cladding (9.62 psf) Solid Wood – 6" Log Walls (17.5 psf)
Moderate	30	Concrete Frame – Light Clad Glass (21.65 psf) Steel Frame – Light Clad Thin Stone (37.60 psf)
Heavy	50	Masonry – Fired Brick – 5" Thin Wall (47.92 psf) Concrete – 6" + Drywall (67.60 psf)
Very heavy	100	Concrete – 8" + Drywall (88.43 psf) Concrete Frame – Brick Infill + Stucco (106.29 psf)

Buildings models were developed in SWORD v6 Beta (Novikova, et al. 2006) according to the Fallout PFs technical report (Dant, et al. 2018) with the following characteristics:

- Roof/floor values (psf) were 5 (wood), 10 (masonry), 30 (concrete), and 100 (concrete)

[1] Live loads include any temporary or transient forces that act on a building or structural element. The live load varies based on occupancy and expected use of a structure or structural element.

- Interior wall mass values (psf) were 10 (very light residential, wood and drywall), 30 (light office/school), and 100
- Percentage of exterior walls that were doors or windows varied from 10% up to 50%.

The models for the 25 types of 1-story buildings have the characteristics presented in Table 2.2.

Table 2.2. Single-story buildings modeled

DTRA Building ID	Ext. Wall (psf)	Roof/Floor (psf)	Apertures (%)	Int. Mass (psf)
A029	1.5	5	10	10
A021	1.5	10	10	10
A020	1.5	30	10	10
A056	1.5	30	25	10
A064	5	10	10	10
A065	5	10	25	10
A035	10	10	10	10
A036	10	10	25	10
A037	10	30	10	10
A051	10	30	10	30
A057	10	30	25	10
A052	10	30	25	30
A091	10	30	50	10
A087	10	30	50	30
A034	10	100	10	10
A066	30	10	10	30
A019	30	30	10	30
A088	30	30	10	100
A090	30	30	25	30
A089	30	30	25	100
A005	100	10	10	100
A094	100	10	25	100
A002	100	30	10	100
A014	100	30	25	100
A013	100	100	10	100

For 2-story buildings there are also 25 various characteristics presented in Table 2.3.

Table 2.3. Two-story buildings modeled

DTRA Building ID	Ext. Wall (psf)	Roof/Floor (psf)	Apertures (%)	Int. Mass (psf)
A025	1.5	10	10	10
A026	1.5	10	25	10
A022	1.5	30	10	10
A061	1.5	30	25	10
A031	10	10	10	10
A030	10	10	10	30
A063	10	10	25	10
A032	10	10	25	30
A062	10	30	10	10
A040	10	30	10	30
A043	10	30	25	10
A041	10	30	25	30
A072	10	30	50	10
A067	10	30	50	30
A023	30	10	10	30
A024	30	10	25	30
A071	30	30	10	30
A068	30	30	10	100
A070	30	30	25	30
A069	30	30	25	100
A004	100	10	10	100
A008	100	10	25	100
A003	100	30	10	100
A007	100	30	25	100
A012	100	50	10	100

The 5-story buildings have 16 variations as presented in Table 2.4.

Table 2.4. Five-story buildings modeled

DTRA Building ID	Ext. Wall (psf)	Roof/Floor (psf)	Apertures (%)	Int. Mass (psf)
A050	10	30	10	10
A048	10	30	10	30
A092	10	30	25	10
A049	10	30	25	30
A086	10	30	50	10
A084	10	30	50	30
A095	30	10	25	30
A085	30	30	10	30
A081	30	30	10	100
A083	30	30	25	30
A082	30	30	25	100
A093	50	10	25	30
A027	100	10	10	100
A028	100	10	25	100
A015	100	30	10	100
A016	100	30	25	100

The 11 variations of 13-story buildings are shown in Table 2.5.

Table 2.5. Thirteen-story buildings modeled

DTRA Building ID	Ext. Wall (psf)	Roof/Floor (psf)	Apertures (%)	Int. Mass (psf)
A047	10	30	10	10
A045	10	30	10	30
A046	10	30	25	10
A080	10	30	25	30
A075	10	30	50	10
A079	10	30	50	30
A078	30	10	25	30
A077	30	30	10	30
A076	30	30	10	100
A053	30	30	25	30
A033	30	30	25	100

The 18 of the buildings were 50 stories tall with the characteristics shown in Table 2.6.

Table 2.6. Fifty-story buildings modeled

DTRA Building ID	Ext. Wall (psf)	Roof/Floor (psf)	Apertures (%)	Int. Mass (psf)
A039	10	10	10	10
A038	10	30	10	10
A044	10	30	10	30
A060	10	30	25	10
A042	10	30	25	30
A074	10	30	50	10
A058	30	10	10	30
A059	30	10	25	30
A017	30	30	10	30
A073	30	30	10	100
A018	30	30	25	30
A054	50	10	10	30
A055	50	10	25	30
A001	100	10	10	100
A010	100	10	25	100
A006	100	30	10	100
A009	100	30	25	100
A011	100	50	10	100

2.3. Computational Method

The simulations were performed with MCNP 6.1.1. For each calculation, two computational runs were performed, one with a prompt neutron source and one with prompt gamma source on the DoD High-Performance Computing (HPC) systems (DoD HPC Modernization Program 1992). On an HPC system, MCNP can take advantage of the message passing interface (mpi) to run in parallel.

In order to reduce the computation time, the simulations were run with weight windows variance-reduction technique that reduced the amount of time spent transporting particles that would not significantly contribute to the final tally count (Goorley 2014).This technique consists on dividing the geometry into many regions and assigns each region a set of numerical bounds that describes the region's importance to the problem. With proper settings of the weights, more particles are transported to the regions of interest and thereby the statistical errors in the calculated doses are decreased for a given number of source particles.

The bounding values of the weight windows were built using the AutomateD VAriaNce reducTion Generator (ADVANTG) software (Mosher, et al. 2015). This code automates the process of generating variance reduction parameters for continuous-energy MCNP simulations. ADVANTG generates space- and energy-dependent mesh-based weight-window bounds and biased source distributions using three-dimensional (3-D) discrete ordinates (S_N) solutions of the adjoint transport equation that are calculated by the Denovo package (Evans, et al. 2010). ADVANTG outputs weight-window lower bounds as an MCNP-compatible weight-window input (WWINP) file. Weight window control parameters and biased source distributions are output as WWP and SB cards, respectively, in an extended version of the user's original MCNP input file.

Rectangular mesh tallies were used in the model to calculate the exposure to prompt radiation. The 1000 ft^2 surface of 1- and 2-story buildings are covered by meshes built on 18 x 18 array of 0.5 m x 0.5 m voxels that are centered at 1 m above floor level. For 5-, 13-, or 50-story buildings, a 54 x 54 array covers the 10,000 ft^2 with the same 0.5 m x 0.5 m dimension of the meshes centered at 1 m above the floor level. Results from MCNP obtained in the form of particle fluence (particles/cm^2) were modified during the calculation with separate energy-dependent dose conversion factors (or response functions) for neutrons and photons. The energy-dependent dose conversion factors assume dose delivered to soft tissue. The individual neutron and gamma doses, from both prompt and secondary gammas from neutron interactions, are considered in this evaluation. Typically the simulation of this scale required over of 10,000 CPU-hours providing statistical relative error less than 5% on all the results[2].

In order to have one set of PFs for the 95 building types we need a prompt source, a location of the source, and a dose suitable for our simulations.

2.4. Prompt Radiation Source

The unclassified leakage spectra from a low-yield thermonuclear sources (Kramer, Dant, et al. 2017) are used for simulations. The prompt spectra for neutron and gammas are presented in Figures 2.2 and 2.3.

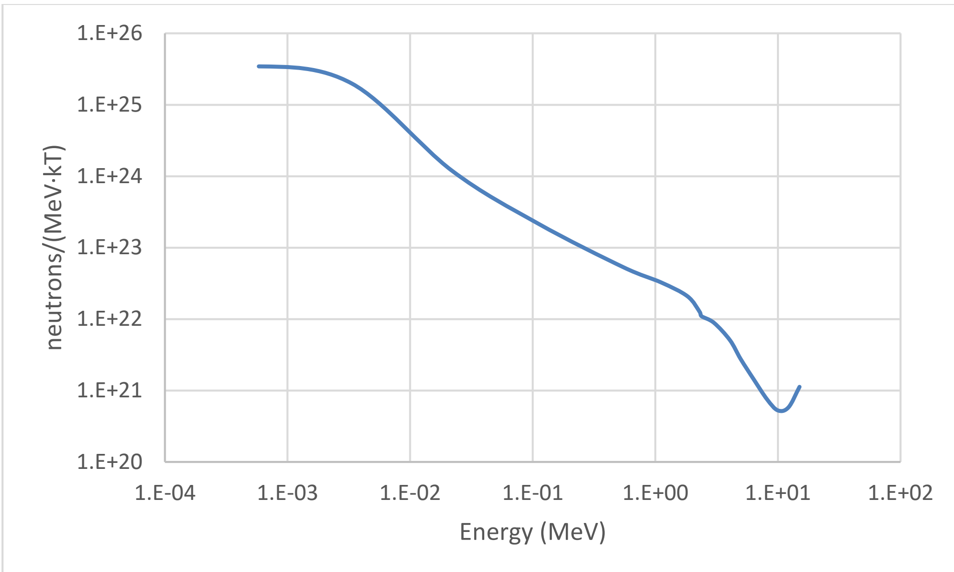

Figure 2.2 Neutron energy spectrum

[2] The relative error, *R*, provides a confidence interval for values *x* obtained via MCNP runs: the estimated 1σ confidence interval is $x(1 \pm R)$.

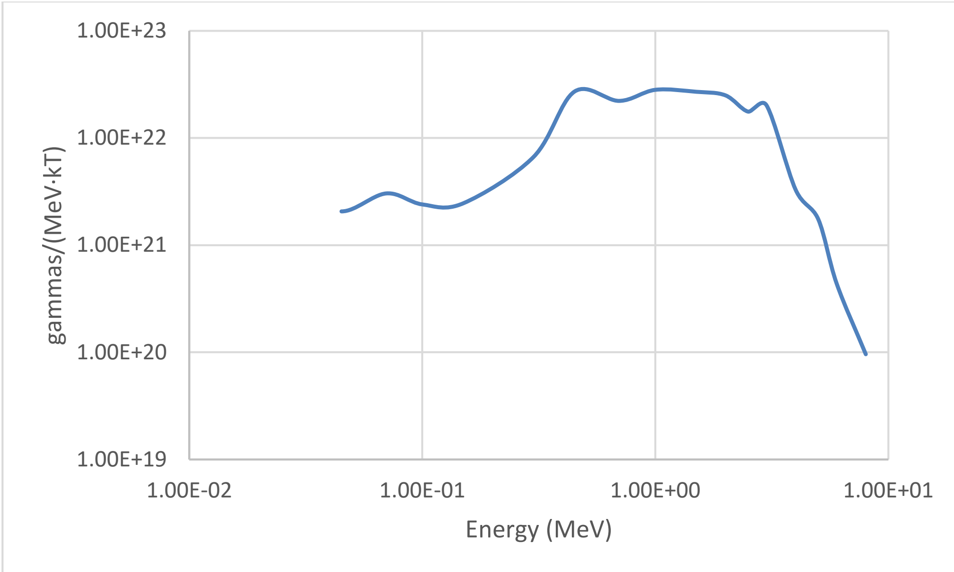

Figure 2.3 Gamma energy spectrum

2.5. Fluence to Dose Conversion Factors

For this work the absorbed soft tissue dose (Gy) was considered the most appropriate dosimetric quantity for evaluation of the PFs as best associated with the possibility of acute, deterministic radiation effects. The use of absorbed dose allows direct comparison of neutron and gamma doses without being modified to account for their relative biological effectiveness (RBE) and it makes the values easier to compare to epidemiological studies (Kramer, Li, et al. 2016).

The effective dose (Sv) was another option for quantifying the PFs but was not considered for this study, being more suitable for estimating longer term, stochastic effects of nuclear radiation. Absorbed soft tissue dose functions from the Radiation Effects Research Foundation (RERF) Hiroshima and Nagasaki Dosimetry in 2002 (Young and Kerr 2005) were used and the features of these conversion factors for neutrons and gammas are shown in Figures 2.4 and 2.5.

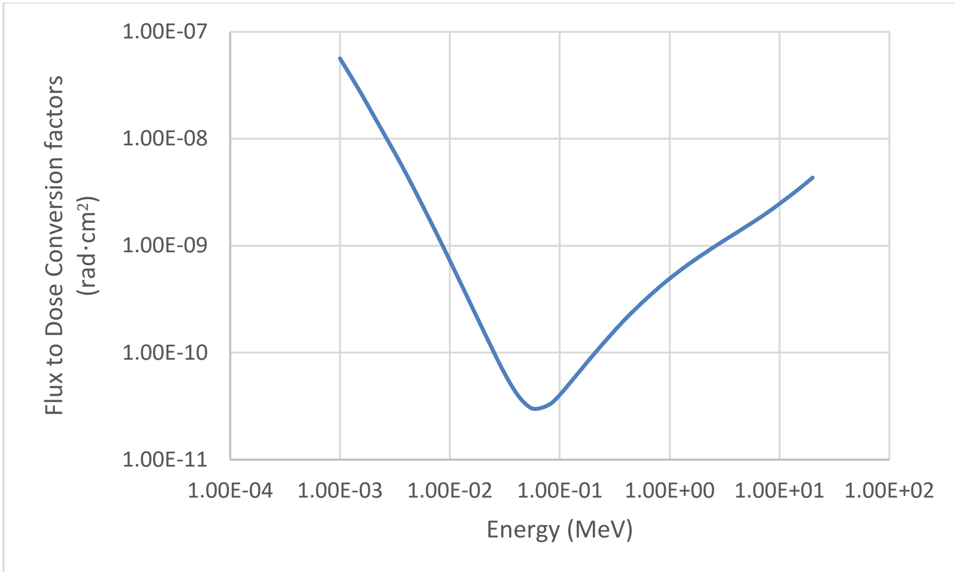

Figure 2.4 Response function for gamma radiation

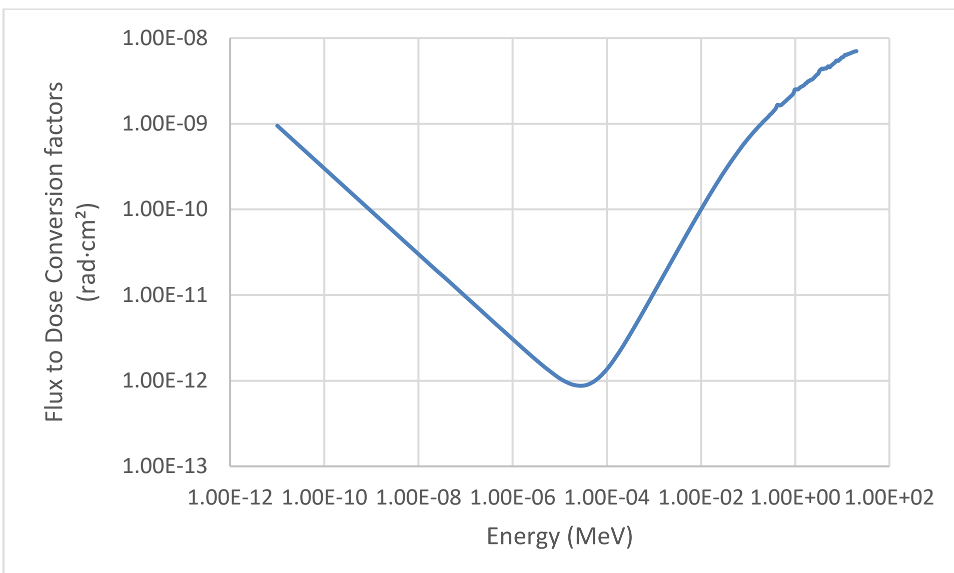

Figure 2.5 Response function for neutron radiation

2.6. Source-Building Distance Sensitivity Study

We decided on spectra for prompt radiation and the dose suitable for our simulations. The following analysis is answering to the question regarding the location of the source.

A hemispherical shell volumetric source in the MCNP model will average out the prompt radiation PFs obtained with sources at different angles at the same distance (radius) from the building as shown in Figure 2.6 where the source is placed at 475 m distance from the building.

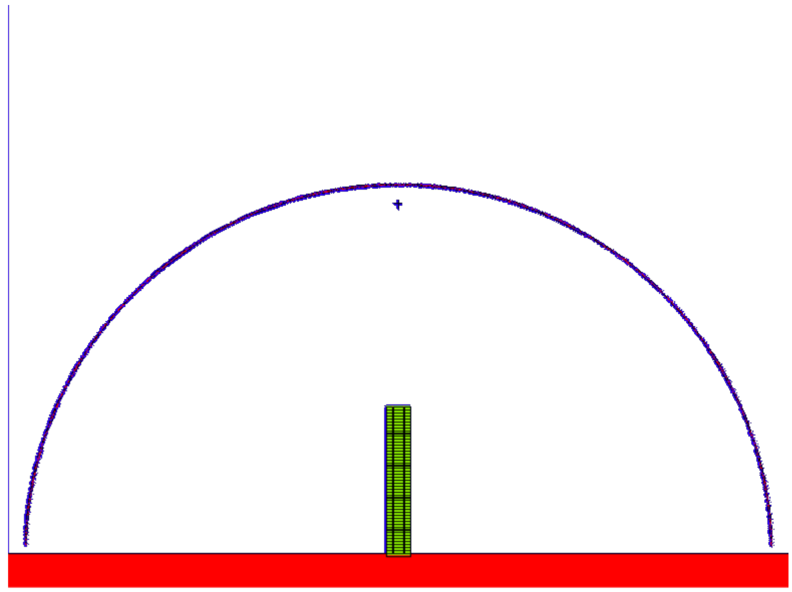

Figure 2.6 Hemispherical shell (R = 475 m) source model example with a 50-story building

A sensitivity study was performed for the 1-, 2-, and 5-story buildings with lowest and highest prompt radiation PFs, considering them representative to analyze the impact on PFs of modifying the radius of the hemispherical source (475 m, 874 m, and 1300 m). The three values explored for the source-building distance correspond to the ranges associated with 10% serious injuries for three yields: 0.1 kt (475 m), 1 kt (874 m), and 10 kt (1300 m) (Jackson and Wright 2013).

Tables 2.7 to 2.12 shows the values obtained for prompt radiation PFs as well as for gammas and neutron PFs, separately. Prompt radiation PF represents the overall PF, summing the effect of both prompt gamma and prompt neutron particles; prompt gammas include the secondary gammas produced by neutron interactions in the atmosphere, ground, and building structures.

The values calculated for PFs are associated with the three scenarios as described in Section 2.1 Protection Factor Calculation:

a. warned population in a building with basement (warned with basement)
b. warned population in a building without basement (warned without basement)
c. unwarned population

The change of the PFs with the distance is very small for cases b) and c). Case a) is more interesting to be analyzed because of the larger changes in the PF values with the distance source-building. The following discussion will refer just to case a), warned with basement.

Table 2.7 shows a decrease of 8.5% for the prompt radiation PFs for the 1-story building with the lowest prompt radiation PF (building characteristics: exterior wall 10 psf, roof 10 psf, 25% aperture, interior wall 10 psf) when increasing the distance building-source from 475 m to 1300 m. The neutrons and gammas have opposite trends: there is 21.4% increase of prompt gamma PF and 4.5% decrease for prompt neutron PF value.

The same analysis was performed for the 1-story building with the highest prompt radiation PF (building characteristics: exterior wall 100 psf, roof 100 psf, 10% aperture, interior wall 100 psf) in Table 2.8. There is a decrease of 14.8% for prompt radiation PF, while the neutron and gammas have similar with previous building example opposite trends: 36.6% increase of prompt gamma PF and 12.4% decrease for neutron PF value. These examples demonstrates the relative insensitivity of the prompt radiation PFs with the building-source distance.

Table 2.7 Prompt PF variation with distance for 1-story building with the lowest PFs

Lowest prompt PF building: exterior wall 10 psf, roof 10 psf, 25% aperture, interior wall 10 psf								
R = 475 m			**R = 804 m**			**R = 1300 m**		
Warned with basement	**Warned without basement**	**Unwarned above ground**	**Warned with basement**	**Warned without basement**	**Unwarned above ground**	**Warned with basement**	**Warned without basement**	**Unwarned above ground**
Prompt PFs			Prompt PFs			Prompt PFs		
4.9	1.6	1.6	4.7	1.6	1.6	4.3	1.5	1.5
Prompt Neutron PFs			Prompt Neutron PFs			Prompt Neutron PFs		
8.9	2.0	2.0	8.9	2.0	2.0	8.5	2.0	2.0
Prompt Gamma PFs			Prompt Gamma PFs			Prompt Gamma PFs		
2.8	1.3	1.3	3.0	1.3	1.3	3.4	1.4	1.4

Table 2.8 Prompt PF variation with distance for 1-story building with the highest PFs

Highest prompt PF building: exterior wall 100 psf, roof 100 psf, 10% aperture, interior wall 100 psf								
R = 475 m			**R = 804 m**			**R = 1300 m**		
Warned with basement	**Warned without basement**	**Unwarned above ground**	**Warned with basement**	**Warned without basement**	**Unwarned above ground**	**Warned with basement**	**Warned without basement**	**Unwarned above ground**
Prompt PFs			Prompt PFs			Prompt PFs		
126.7	7.4	7.4	120.4	7.3	7.3	108.0	7.1	7.1
Prompt Neutron PFs			Prompt Neutron PFs			Prompt Neutron PFs		
639.6	15.9	15.9	634.2	16.0	16.0	560.3	15.2	15.2
Prompt Gamma PFs			Prompt Gamma PFs			Prompt Gamma PFs		
53.5	4.0	4.0	60.1	4.5	4.5	73.6	5.6	5.6

A further investigation for taller buildings shows that the trend doesn’t change. For 2-story buildings (Table 2.9 and Table 2.10) there is a 7.8% decrease for prompt radiation PFs for the building with lowest PF (building characteristics: exterior wall 10 psf, roof 10 psf, 25% aperture, interior wall 10 psf) and 10.4% for the building with highest prompt radiation PF (building characteristics: exterior wall 100 psf, roof 30 psf, 10% aperture, interior wall 100 psf). Gamma radiation PFs have a high increase in PFs: 28.6% for lowest PF building and 43.6% for highest PF building. On the neutron’s side the PFs are slightly decreasing by 3.2% for the lowest PF 2-story building and by 9.7% for the highest PF 2-story building.

Table 2.9 Prompt PF variation with distance for 2-story building with the lowest PFs

Lowest prompt PF building: exterior wall 10 psf, roof 10 psf, 25% aperture, interior wall 10 psf										
R = 475 m				**R = 804 m**				**R = 1300 m**		
Warned with basement	**Warned without basement**	**Unwarned above ground**		**Warned with basement**	**Warned without basement**	**Unwarned above ground**		**Warned with basement**	**Warned without basement**	**Unwarned above ground**
Prompt PFs				Prompt PFs				Prompt PFs		
5.1	1.7	1.5		5.0	1.7	1.5		4.7	1.6	1.5
Prompt Neutron PFs				Prompt Neutron PFs				Prompt Neutron PFs		
9.5	2.1	1.9		9.6	2.1	2.0		9.2	2.1	1.9
Prompt Gamma PFs				Prompt Gamma PFs				Prompt Gamma PFs		
2.8	1.2	1.1		3.0	1.3	1.2		3.6	1.4	1.3

Table 2.10 Prompt PF variation with distance for 2-story building with the highest PFs

Highest prompt PF building: exterior wall 100 psf, roof 30 psf, 10% aperture, interior wall 100 psf										
R = 475 m				**R = 804 m**				**R = 1300 m**		
Warned with basement	**Warned without basement**	**Unwarned above ground**		**Warned with basement**	**Warned without basement**	**Unwarned above ground**		**Warned with basement**	**Warned without basement**	**Unwarned above ground**
Prompt PFs				Prompt PFs				Prompt PFs		
107.3	9.2	6.5		103.8	9.0	6.4		96.1	8.9	6.3
Prompt Neutron PFs				Prompt Neutron PFs				Prompt Neutron PFs		
489.5	20.0	12.6		489.8	20.2	12.7		442.2	19.4	12.2
Prompt Gamma PFs				Prompt Gamma PFs				Prompt Gamma PFs		
44.5	4.6	3.5		50.8	5.2	3.8		63.9	6.6	4.8

In the same way two 5-story buildings have been investigated (Tables 2.11 and 2.12). The overall prompt radiation PFs decreased with the distance from the source by 9.2% (the lowest PF building: exterior wall 10 psf, roof 30 psf, 50% aperture, interior wall 10 psf) and by 3.8% (the highest PF building: exterior wall 100 psf, roof 30 psf, 10% aperture, interior wall 100 psf). The neutron PFs decreased by 5.1% (lowest PF building) and by 5.6% (highest PF building) while gamma PFs increase by 40% (lowest PF building) and by 49.7% (highest PF building).

Table 2.11 Prompt PF variation with distance for 5-story building with the lowest PFs

Lowest prompt PF building: exterior wall 10 psf, roof 30 psf, 50% aperture, interior wall 10 psf										
R = 475 m				**R = 804 m**				**R = 1300 m**		
Warned with basement	**Warned without basement**	**Unwarned above ground**		**Warned with basement**	**Warned without basement**	**Unwarned above ground**		**Warned with basement**	**Warned without basement**	**Unwarned above ground**
Prompt PFs				Prompt PFs				Prompt PFs		
13.1	3.7	2.9		12.7	3.7	2.9		11.9	3.6	2.8
Prompt Neutron PFs				Prompt Neutron PFs				Prompt Neutron PFs		
37.2	5.5	3.8		37.6	5.6	3.8		35.3	5.5	3.7
Prompt Gamma PFs				Prompt Gamma PFs				Prompt Gamma PFs		
6.0	2.3	1.7		6.8	2.6	1.9		8.4	3.0	2.2

Table 2.12 Prompt PF variation with distance for 5-story building with the highest PFs

Highest prompt PF building: exterior wall 100 psf, roof 30 psf, 10% aperture, interior wall 100 psf										
R = 475 m				**R = 804 m**				**R = 1300 m**		
Warned with basement	**Warned without basement**	**Unwarned above ground**		**Warned with basement**	**Warned without basement**	**Unwarned above ground**		**Warned with basement**	**Warned without basement**	**Unwarned above ground**
Prompt PFs				Prompt PFs				Prompt PFs		
151.1	24.5	11.3		149.1	24.5	11.3		145.4	24.2	11.1
Prompt Neutron PFs				Prompt Neutron PFs				Prompt Neutron PFs		
470.6	47.0	16.6		474.3	47.9	16.7		442.4	46.2	16.1
Prompt Gamma PFs				Prompt Gamma PFs				Prompt Gamma PFs		
67.8	13.3	6.4		78.1	15.1	7.2		101.5	18.8	8.8

The analysis shows that the change in the source-building distance has a higher impact on gamma PFs (up to 49% increase) comparing with neutron PFs (up to 12.4 % decrease) at the basement level; the maximum impact will be on buildings with high PFs. The prompt radiation PFs that sums the effect of both prompt neutrons and gammas are consistently decreasing with distance but with a relative small amount, less than 15%.

Based on the above results we can conclude that the minimum distance of 475 m is our conservative solution considering the computational effort and small variation in the prompt radiation PFs when increasing the radius (source-building distance).

2.7. Angular Location Sensitivity Study

Another set of simulations was proposed using the same set of 1-, 2-, and 5-story buildings (with lowest and highest prompt radiation PFs) for analyzing the variation of the prompt radiation PFs with angular location. PFs were calculated for three different locations of a point source and compare with the value obtained with the hemispherical shell source of 475 m radius which averages the angular location variation. The locations are: close to the ground at 10 m height (0º) at 475 m distance to the building, at 475 m height of burst (90º), and at 45º angle at the same 475 m distance from the building.

Similar with previous analysis, from the three scenarios described in Section 2.1 Protection Factor Calculation a) warned with basement, b) warned without basement, c) unwarned population, the basement PFs associated with scenario a) show the most significant variation with locations so they are more interesting for being analyzed.

An example of calculation of the PFs for scenario a) warned with basement is presented in Table 2.13 for 1-story building with the lowest PFs (building characteristics: exterior wall 10 psf, roof 10 psf, 25% aperture, interior wall 10 psf). The doses are received for 0.1 kt in this example and for the three locations we have three different values for D_0, the reference absorbed soft tissue dose in the open; for comparison a value corresponding to using hemispherical shell source is also included. The table contains also the average values for the absorbed soft tissue dose received in the basement and the PFs which are the ratio of the dose received in the open to the dose received inside the building, in the basement in our case.

Table 2.13 Prompt PF variation with location for 1-story building with the lowest PFs

Absorbed soft tissue dose in rad(tissue) in the open for 0.1 kt yield at 475 m				
contributors	**Hemispherical shell source**	**Point source at 0º**	**Point source at 45º**	**Point source at 90º**
prompt neutrons	332.3	164.3	385.7	428.1
gamma (pr + sec)	183.6 (39.0 + 144.6)	96.9 (28.7 + 68.2)	213.0 (41.3 + 171.7)	244.5 (42.3 + 202.2)
Total D_0	515.9	261.0	598.7	672.5
Absorbed soft tissue dose in rad(tissue) in basement for 0.1 kt yield at 475 m				
neutrons	37.4	13.2	46.6	64.9
gammas (pr + sec)	68.9	21.4	87.8	116.5
Total $D_{avg,bas}$	106.3	34.6	134.4	181.4
PFs for warned with basement scenario				
neutron PFs	8.9	12.5	8.3	6.6
gammas PFs	2.8	4.7	2.5	2.2
Prompt Rad PFs	4.9	7.6	4.5	3.7

In Table 2.13 one can see the prompt radiation PF ranging from 3.7 (source at 90º) to 7.6 (source at 0º) and the average value for PF is 4.9 and was obtained with a hemispheric shell source. The variation of prompt neutron and gamma PFs are presented in similar way: neutron PFs with higher values than gamma PFs having maximum values of 12.5 (source at 0º) and minimum value 6.6 (source at 90º) and gamma PFs with maximum of 4.7 (source at 0º) and minimum of 2.2 (source at 90º). The average values obtained with a hemispherical shell source are for neutrons, 8.9 and for gammas, 2.8.

Tables 2.14 to 2.18 show the values of the PFs in the similar way. The maximum values for PFs are obtained when the source is close to the ground (at 0º) at and lowest values are observed when the source is located at a 475 m height of burst or 90º. The only exception is the 5-story building with the lowest prompt radiation PF (Table 2.17), where the lowest values for PFs are observed with the source at 45º.

The variation of the PFs with the source location for 1-story building with the highest PFs (building characteristics: exterior wall 100 psf, roof 100 psf, 10% aperture, interior wall 100 psf) is presented in Table 2.14 and this is the warned with basement scenario summary:

- prompt radiation PFs ranging from 87.2 (source at 90º) to 200.6 (source at 0º); the average PF is 126.7 and was obtained with a hemispheric shell source
- prompt neutron PFs ranging from 371.4 (source at 90º) to 914.8 (source at 0º); the average PF is 639.6
- prompt gamma PFs ranging from 38.6 (source at 90º) to 89.3 (source at 0º); the average PF is 53.5

Table 2.14 Prompt PF variation with location for 1-story building with the highest PFs

Highest prompt PF building: exterior wall 100 psf, roof 100 psf, 10% aperture, interior wall 100 psf				
Warned with basement scenario				
contributors	**Hemispherical shell source**	**Point source at 0º**	**Point source at 45º**	**Point source at 90º**
neutron PFs	639.6	914.8	680.9	371.4
gammas PFs	53.5	89.3	51.2	38.6
Prompt Rad PFs	126.7	200.6	122.8	87.2

For 2-story buildings we have the same analysis. The variation of the PFs with the source location for 2-story building with the lowest PFs (building characteristics: exterior wall 10 psf, roof 10 psf, 25% aperture, interior wall 10 psf) is presented in Table 2.15 and this is the warned with basement scenario summary:

- prompt radiation PFs ranging from 4.2 (source at 90°) to 7.6 (source at 0°); the average PF is 5.1 and was obtained with a hemispheric shell source
- prompt neutron PFs ranging from 7.9 (source at 90°) to 12.8 (source at 0°); the average PF is 9.5
- prompt gamma PFs ranging from 2.3 (source at 90°) to 4.5 (source at 0°); the average PF is 2.8

Table 2.15 Prompt PF variation with location for 2-story building with the lowest PFs

Lowest prompt PF building: exterior wall 10 psf, roof 10 psf, 25% aperture, interior wall 10 psf				
Warned with basement scenario				
contributors	**Hemispherical shell source**	**Point source at 0°**	**Point source at 45°**	**Point source at 90°**
neutron PFs	9.5	12.8	8.8	7.9
gammas PFs	2.8	4.5	2.5	2.3
Prompt Rad PFs	5.1	7.6	4.7	4.2

The variation of the PFs with the source location for 2-story building with the highest PFs (building characteristics: exterior wall 100 psf, roof 30 psf, 10% aperture, interior wall 100 psf) is presented in Table 2.16 and this is the warned with basement scenario summary:

- prompt radiation PFs ranging from 79.2 (source at 90°) to 159.8 (source at 0°); the average PF is 107.3 and was obtained with a hemispheric shell source
- prompt neutron PFs ranging from 323.6 (source at 90°) to 637.0 (source at 0°); the average PF is 489.5
- prompt gamma PFs ranging from 34.1 (source at 90°) to 70.4 (source at 0°); the average PF is 44.5

Table 2.16 Prompt PF variation with location for 2-story building with the highest PFs

Highest prompt PF building: exterior wall 100 psf, roof 30 psf, 10% aperture, interior wall 100 psf				
Warned with basement scenario				
contributors	**Hemispherical shell source**	**Point source at 0°**	**Point source at 45°**	**Point source at 90°**
neutron PFs	489.5	637.0	558.0	323.6
gammas PFs	44.5	70.4	43.0	34.1
Prompt Rad PFs	107.3	159.8	106.1	79.2

The variation of the PFs with the source location for 5-story building with the lowest PFs (building characteristics: exterior wall 10 psf, roof 30 psf, 50% aperture, interior wall 10 psf) is presented in Table 2.17 and in this case minimum PF for the warned with basement scenario is at 45° not at 90°. This case is different because the materials used for the exterior walls (10 psf) are less protective comparing with the material used for roof (30 psf) and when the buildings are taller the exterior wall have higher impact on PFs than the roof. This is a summary for this building:

- prompt radiation PFs ranging from 12.2 (source at 45°) to 17.6 (source at 0°); the average PF is 13.1 and was obtained with a hemispheric shell source

- prompt neutron PFs ranging from 34.2 (source at 45º) to 42.4 (source at 0º); the average PF is 37.2
- prompt gamma PFs ranging from 5.6 (source at 45º) to 8.8 (source at 0º); the average PF is 6.0

Table 2.17 Prompt PF variation with location for 5-story building with the lowest PFs

Lowest prompt PF building: exterior wall 10 psf, roof 30 psf, 50% aperture, interior wall 10 psf				
Warned with basement scenario				
contributors	**Hemispherical shell source**	**Point source at 0º**	**Point source at 45º**	**Point source at 90º**
neutron PFs	37.2	42.4	34.2	46.3
gammas PFs	6.0	8.8	5.6	6.1
Prompt Rad PFs	13.1	17.6	12.2	13.6

The variation of the PFs with the source location for 5-story building with the highest PFs (building characteristics: exterior wall 100 psf, roof 30 psf, 10% aperture, interior wall 100 psf) is presented in Table 2.18 and this is the warned with basement scenario summary:

- prompt radiation PFs ranging from 120.4 (source at 90º) to 200.0 (source at 0º); the average PF is 151.1 and was obtained with a hemispheric shell source
- prompt neutron PFs ranging from 398.2 (source at 90º) to 513.7 (source at 0º); the average PF is 470.6
- prompt gamma PFs ranging from 54.1 (source at 90º) to 98.1 (source at 0º); the average PF is 67.8

Table 2.18 Prompt PF variation with location for 5-story building with the highest PFs

Lowest prompt PF building: exterior wall 10 psf, roof 30 psf, 50% aperture, interior wall 10 psf				
Warned with basement scenario				
contributors	**Hemispherical shell source**	**Point source at 0º**	**Point source at 45º**	**Point source at 90º**
neutron PFs	470.6	513.7	454.3	398.2
gammas PFs	67.8	98.1	64.1	54.1
Prompt Rad PFs	151.1	200.0	143.7	120.4

The above results show the variation of the prompt PF with angular location of the source. The analysis provides a good understanding of the way the location of the source influence the PF values. Since the goal is to calculate PFs which will be used by HPAC, it was decided to use the hemispherical shell volumetric source of 475 m radius for all calculations to provide an average PF over all source angles.

Section 3. Results

Tables 3.1 to 3.5 summarize the prompt radiation PFs, including values for neutron and gammas separately, calculated for 95 building types considering three scenarios:

a. warned population in a building with basement (warned with basement) considering the population occupying the building all having moved to the basement
b. warned population in a building without basement (warned without basement) considering the population occupying the building all having moved to the first floor
c. unwarned population with the population occupying the building distributed equally on all of the above ground floors

The values to be used in HPAC 6.5 are highlighted in yellow. Based on building height it is assumed that a basement is present for 13- and 50-story buildings.

Table 3.1. PFs for 1-story buildings

	Neutron PFs			Gamma PFs			Prompt Radiation PFs		
DTRA Building ID	Warned with basement	Warned without basement	Unwarned above ground	Warned with basement	Warned without basement	Unwarned above ground	Warned with basement	Warned without basement	Unwarned above ground
A029	9.3	1.9	1.9	3.1	1.3	1.3	5.3	1.6	1.6
A021	9.0	2.1	2.1	3.1	1.4	1.4	5.3	1.7	1.7
A020	16.4	2.0	2.0	4.3	1.4	1.4	8.0	1.7	1.7
A056	16.4	2.0	2.0	4.3	1.4	1.4	8.0	1.7	1.7
A064	10.3	2.4	2.4	3.2	1.4	1.4	5.7	1.8	1.8
A065	10.6	2.4	2.4	3.3	1.4	1.4	5.8	1.8	1.8
A035	8.8	2.0	2.0	2.8	1.3	1.3	4.9	1.6	1.6
A036	8.9	2.0	2.0	2.8	1.3	1.3	4.9	1.6	1.6
A037	16.2	1.9	1.9	3.9	1.3	1.3	7.5	1.6	1.6
A051	21.6	2.3	2.3	4.6	1.3	1.3	9.2	1.8	1.8
A057	16.4	2.0	2.0	3.9	1.3	1.3	7.4	1.6	1.6
A052	21.5	2.3	2.3	4.7	1.4	1.4	9.2	1.8	1.8
A091	16.3	2.0	2.0	3.9	1.3	1.3	7.5	1.6	1.6
A087	21.4	2.3	2.3	4.7	1.4	1.4	9.2	1.8	1.8
A034	93.4	2.6	2.6	10.7	1.4	1.4	24.1	1.9	1.9
A066	17.8	3.5	3.5	4.4	1.7	1.7	8.3	2.4	2.4
A019	31.5	3.5	3.5	6.2	1.7	1.7	12.6	2.4	2.4
A088	43.1	4.2	4.2	10.3	2.2	2.2	19.7	3.0	3.0
A090	29.4	3.1	3.1	6.0	1.7	1.7	12.1	2.3	2.3
A089	20.9	3.8	3.8	6.1	2.1	2.1	10.9	2.8	2.8
A005	33.4	6.6	6.6	9.4	2.9	2.9	17.1	4.3	4.3
A094	15.9	5.3	5.3	5.4	2.6	2.6	9.2	3.7	3.7
A002	60.5	6.5	6.5	13.8	2.9	2.9	26.8	4.4	4.4
A014	29.3	5.3	5.3	7.7	2.6	2.6	14.3	3.7	3.7
A013	639.6	15.9	15.9	53.5	4.0	4.0	126.7	7.4	7.4

MCNP results with Statistical Relative Error less than 2%.

Table 3.2. PFs for 2-story buildings

	Neutron PFs			Gamma PFs			Prompt Radiation PFs		
DTRA Building ID	Warned with basement	Warned without basement	Unwarned above ground	Warned with basement	Warned without basement	Unwarned above ground	Warned with basement	Warned without basement	Unwarned above ground
A025	9.7	2.2	2.0	3.1	1.3	1.2	5.6	1.8	1.6
A026	9.6	2.2	2.0	3.1	1.3	1.2	5.5	1.8	1.6
A022	46.6	2.6	2.4	7.2	1.4	1.3	15.8	2.0	1.8
A061	46.4	2.6	2.4	7.2	1.4	1.3	15.7	2.0	1.8
A031	9.6	2.1	1.9	2.7	1.2	1.1	5.1	1.7	1.5
A030	13.0	2.5	2.3	3.3	1.3	1.2	6.4	1.9	1.7
A063	9.5	2.1	1.9	2.8	1.2	1.1	5.1	1.7	1.5
A032	13.0	2.5	2.3	3.4	1.3	1.2	6.4	1.9	1.7
A062	48.0	2.6	2.3	6.6	1.3	1.2	14.8	1.9	1.7
A040	62.4	2.9	2.7	8.1	1.4	1.3	18.5	2.1	1.9
A043	47.6	2.5	2.3	6.6	1.3	1.2	14.8	1.9	1.7
A041	61.8	2.9	2.7	8.1	1.4	1.3	18.5	2.1	1.9
A072	46.9	2.5	2.3	6.6	1.3	1.2	14.8	1.9	1.8
A067	61.0	2.9	2.6	8.2	1.4	1.3	18.5	2.1	2.0
A023	24.6	4.6	3.8	5.0	1.8	1.5	10.2	2.9	2.5
A024	21.8	4.0	3.3	4.7	1.7	1.5	9.5	2.7	2.3
A071	119.5	5.8	4.9	12.9	2.0	1.7	30.3	3.4	2.9
A068	172.9	7.1	5.9	22.2	2.6	2.2	50.5	4.4	3.7
A070	104.3	4.8	4.2	12.0	1.9	1.6	27.8	3.1	2.7
A069	73.5	5.9	5.1	12.1	2.4	2.1	26.1	3.9	3.4
A004	67.8	12.9	8.1	13.9	3.8	2.9	28.5	7.0	4.9
A008	25.8	8.5	6.2	7.2	3.2	2.5	13.5	5.3	4.1
A003	489.5	20.0	12.6	44.5	4.6	3.5	107.3	9.2	6.5
A007	159.3	11.2	8.7	20.3	3.7	3.0	45.7	6.5	5.2
A012	355.2	18.9	11.3	36.6	4.5	3.3	86.6	8.8	6.1

MCNP results with Statistical Relative Error less than 2%.

Table 3.3. PFs for 5-story buildings

	Neutron PFs			Gamma PFs			Prompt Radiation PFs		
DTRA Building ID	Warned with basement	Warned without basement	Unwarned above ground	Warned with basement	Warned without basement	Unwarned above ground	Warned with basement	Warned without basement	Unwarned above ground
A050	38.0	5.5	3.8	6.0	2.3	1.6	13.2	3.7	2.8
A048	66.6	7.6	5.3	10.9	3.3	2.2	23.7	5.1	3.9
A092	37.6	5.5	3.8	6.0	2.3	1.7	13.1	3.7	2.9
A049	65.9	7.5	5.3	10.9	3.3	2.2	23.6	5.1	3.9
A086	37.2	5.5	3.8	6.0	2.3	1.7	13.1	3.7	2.9
A084	65.4	7.5	5.3	10.9	3.3	2.3	23.5	5.1	3.9
A095	54.0	11.2	6.8	9.2	3.8	2.4	19.8	6.7	4.5
A085	138.3	15.3	8.8	17.5	4.7	2.9	40.1	8.5	5.4
A081	168.5	17.1	9.7	32.8	7.1	4.4	68.2	11.4	7.4
A083	118.0	12.7	7.8	16.0	4.4	2.7	36.1	7.6	5.1
A082	145.2	14.4	8.7	30.0	6.6	4.2	61.4	10.1	6.9
A093	56.9	11.7	6.9	10.2	4.4	2.6	21.6	7.3	4.8
A027	183.8	38.5	14.2	37.4	11.8	5.7	76.8	21.3	10.1
A028	122.8	23.3	11.2	28.7	9.4	5.0	56.7	15.3	8.6
A015	470.6	47.0	16.6	67.8	13.3	6.4	151.1	24.5	11.3
A016	296.0	27.0	12.9	49.6	10.2	5.5	107.1	17.0	9.5

MCNP results with Statistical Relative Error less than 5%.

Table 3.4. PFs for 13-story buildings

	Neutron PFs			Gamma PFs			Prompt Radiation PFs		
DTRA Building ID	Warned with basement	Warned without basement	Unwarned above ground	Warned with basement	Warned without basement	Unwarned above ground	Warned with basement	Warned without basement	Unwarned above ground
A047	39.1	5.6	3.7	6.5	2.5	1.7	14.1	3.9	2.7
A045	68.0	7.7	5.2	11.6	3.5	2.3	25.0	5.4	3.7
A046	67.5	7.7	5.2	11.6	3.5	2.3	24.9	5.4	3.7
A080	38.3	5.6	3.7	6.5	2.5	1.7	14.0	3.9	2.7
A075	67.0	7.7	5.1	11.6	3.5	2.3	24.8	5.4	3.7
A079	142.5	15.6	9.5	18.8	5.0	3.1	42.6	8.9	5.6
A078	173.9	17.5	10.5	34.9	7.5	4.8	71.9	11.8	7.5
A077	121.3	13.0	8.2	17.1	4.6	2.9	38.3	7.9	5.1
A076	149.4	14.7	9.2	31.9	7.0	4.5	64.7	10.5	6.9
A053	498.8	48.1	22.5	73.9	14.1	7.6	163.8	25.9	13.5
A033	309.8	27.8	15.6	53.6	10.9	6.3	114.8	17.9	10.4

MCNP results with Statistical Relative Error less than 5%.

Table 3.5. PFs for 50-story buildings

	Neutron PFs			Gamma PFs			Prompt Radiation PFs		
DTRA Building ID	Warned with basement	Warned without basement	Unwarned above ground	Warned with basement	Warned without basement	Unwarned above ground	Warned with basement	Warned without basement	Unwarned above ground
A039	16.4	4.7	1.9	3.9	2.2	1.0	7.7	3.4	1.4
A038	40.1	5.8	2.5	7.0	2.7	1.2	14.9	4.1	1.8
A044	70.2	8.0	3.5	12.5	3.7	1.7	26.6	5.7	2.5
A060	39.6	5.8	2.5	7.0	2.7	1.2	14.8	4.1	1.8
A042	69.5	7.9	3.4	12.5	3.7	1.7	26.5	5.6	2.5
A074	39.2	5.7	2.5	7.0	2.7	1.2	14.8	4.1	1.8
A058	71.8	14.6	5.6	12.1	4.8	2.0	26.1	8.5	3.4
A059	59.6	12.2	4.8	10.5	4.5	1.9	22.3	7.6	3.1
A017	145.9	16.0	6.7	20.0	5.3	2.3	45.0	9.3	4.0
A073	178.2	18.0	7.5	37.2	8.0	3.5	75.9	12.4	5.4
A018	124.5	13.4	5.7	18.3	4.9	2.2	40.6	8.3	3.6
A054	78.4	15.5	5.8	13.7	5.7	2.3	29.2	9.6	3.8
A055	64.0	12.5	4.9	12.4	5.1	2.1	25.9	8.2	3.4
A001	243.8	44.5	15.8	49.2	14.4	5.3	101.3	25.5	9.3
A010	150.4	26.1	10.0	36.2	11.2	4.3	70.9	17.7	6.8
A006	514.8	49.7	19.2	78.8	15.0	5.8	173.4	27.3	10.6
A009	317.6	28.7	12.1	57.5	11.6	4.7	121.7	18.9	7.8
A011	898.7	51.5	22.0	112.8	15.6	6.4	258.4	28.3	11.8

MCNP results with Statistical Relative Error less than 10%.

Section 4. Conclusions

As part of the effort to improve the HPAC consequence assessment, the protection factor values for 95 building types have been calculated.

It is important to understand the limitation of this work; the values of the protection factors depend on the prompt spectra used as radiation source for simulations. In this project we used unclassified low yield thermonuclear spectra. However, the PFs can be evaluated using the energy bins over which the spectra are specified, as neutron (and gamma) standalone sources. In this way any spectrum can be reassembled, the doses in the open and in the buildings can be calculated, and the PFs can be evaluated for different spectra. This methodology allows also unclassified runs to be used in classified environment. This generalization could be part of future work.

Section 5. References

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Section 6. Abbreviations, Acronyms, and Symbols

ADVANTG	AutomateD VAriaNce reducTion Generator
ARA	Applied Research Associates, Inc.
CBRN	Chemical Biological Radiological & Nuclear
DS02	Dosimetry Systems 2002
DTRA	Defense Threat Reduction Agency
HPAC	Hazard Prediction and Assessment Capability
LLNL	Lawrence Livermore National Laboratory
HPC	High Performance Computing
MCNP	Monte Carlo N-Particle
ORNL	Oak Ridge National Laboratory
PF	Protection Factors
psf	pounds per square foot
SWORD	Software for the Optimization of Radiation Detectors